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ABSTRACT

Recent research findings concerning analysis of covariance (ANCOVA) are reviewed, its use is illustrated, and a method for performing it using the Statistical Package for the Social Sciences is presented. In addition, methods for examining Elashoff's seven assumptions as a prerequisite to the correct application of ANCOVA are discussed. Specifically, the assumptions are: (1) that cases are assigned randomly to treatment conditions: (2) that the covariate is independent of the treatment effect: (3) that the covariate is measured without error: (4) that the covariate is linearly related to the dependent variable: (5) that the regression of the dependent variable on the covariate is the same for each group: (6) that for each level of the covariate, the dependent variable is normally distributed: (7) that the variance of the dependent variable at a given value of the covariate is constant across treatment groups and is independent of the covariate. ANCOVA can be performed very easily when the assumptions are kept in mind from the onset, but if one or more of the critical assumptions are not met, alternative types of analysis should be considered. (RL)

The Care and Feeding of ANCOVA

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Presented at the Annual Meeting

of the

Mid-South Education Research Association

in

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Abstract

The question, when and if to use analysis of covariance, has been debated for the past 15 years. The purposes of this paper are to review recent research findings concerning analysis of covariance, illustrate how it is used including tests of the assumptions, and suggest alternatives when specific assumptions are not met. The paper also illustrates how to perform analysis of covariance using the Statistical Package for the Social Sciences.

The Care and Feeding of ANCOVA

The last 15 years have brought much controversy regarding analysis of covariance (ANCOVA). Many researchers in education are not sure when or if it should be used, and if they use it, they are not sure exactly how. The purposes of this paper are to review recent research findings concerning when to use analysis of covariance, to illustrate how it is used including the tests of assumptions, and to suggest alternatives when specific assumptions are not met.

Background

ANCOVA was derived originally by Fisher (1932) and has generated a lot of interest since that time. An entire 1957 issue of Biometrics was devoted to a consideration of ANCOVA. Over the years, two major functions have been attributed to ANCOVA:

(1) An increase in the precision of an experiment, through reduction of unexplained within cell variation, and

(2) A correction for initial differences among groups by adjusting criterion scores for some independent variable(s).

A frequent use of ANCOVA in educational research is for analyzing data from a pretest-posttest-control group design when there are initial differences between the groups. It is assumed that, as the second function indicates, ANCOVA will overcome the initial difference problem. Investigation demonstrated that ANCOVA will not statistically correct this problem. Lord (1956, 1960, & 1969), Campbell and Erlebacher (1970), and Cronbach and Furby (1970) among others have recognized this fact.

Horst, Tallmadge, and Wood (1974) and Tallmadge and Horst (1976) went beyond a warning of caution and incorrectly suggested that ANCOVA was unjustified under certain conditions:

> There is, of course, no justification for the extra computational labor required for covariance analysis if the two groups obtained equal scores on the pretest. (Tallmadge & Horst, 1976, p. 46)

This misleading and overly simplified conclusion has been echoed by Becker and Engelmann (1976).

Careful research has shown that ANCOVA can be a very useful procedure to increase the sensitivity of an analysis if applied correctly (McLean & Ware, 1977; Ware & McLean, 1978). A correct application of ANCOVA requires the examination of a number of assumptions. Elashoff (1969) identified seven assumptions and indicated that the interpretation of ANCOVA results was dependent upon the degree to which these assumptions were met. Results of other studies (Glass, Peckham, & Sanders, 1972; McLean, 1974; McLean, 1977) have indicated the relative importance and/or robustness of the various assumptions.

The remainder of the paper examines methods for testing each of the ANCOVA assumptions, illustrates an analysis, and suggests possible alternative analyses.

Testing Assumptions

Using ANCOVA usually requires meeting the three assumptions customary to analysis of variance (random sampling, normality, and homogeneity of variance) plus four others (Elashoff, 1969). Specifically, the assumptions outlined by Elashoff are as follows:

(1) that cases are assigned randomly to treatment conditions,

(2) that the covariate is independent of the treatment effect,

(3) that the covariate is measured without error (i.e., with perfect reliability),

(4) that the covariate is linearly related to the dependent variable,

(5) that the regression of the dependent variable on the covariate is the same for each group,

(6) that for each level of the covariate, the dependent variable is normally distributed, and

(7) that the variance of the dependent variable at a given value of the covariate is constant across treatment groups and is independent of the covariate.

The relative importance and appropriate test (if necessary) of each assumption follows.

Random Assignment

Random sampling is basic to every inferential statistical procedure. The F probability distribution was derived on the basis of random assignment. Although it is called an assumption, random sampling can be designed into an experiment and its implementation physically checked.

Random assignment per se is not even mentioned in the now classic article, "Consequences of Failure to Meet Assumptions Underlying the Fixed Effects Analysis of Variance and Covariance" (Glass et al., 1972). However, violation of this assumption often manifests itself in the failure to meet one or more of the other six assumptions.

Independence of Covariate and Treatment

This assumption may be the most important single assumption in ANCOVA. If the covariate and the treatments are independent, one would not expect the covariate means for each treatment group to differ significantly. An easy test of this assumption would involve comparing the covariate means of the groups by performing an analysis of variance on the covariates while ignoring the dependent variables. Rejection of the null hypothesis would indicate that the assumption is not met, while non-rejection would indicate that there is no reason to believe that the assumption had been violated.

Perfect Reliability

It is obvious that measurement with perfect reliability in the social sciences is impossible. A requirement that this assumption be met would invalidate nearly all of the research of the last 50 years which used the least squares model. A previous study (McLean, 1974) indicated that if the assumption concerning independence of the covariate and treatment is met, the assumption of perfect reliability becomes less important.

Covariate Related to Dependent Variable

The assumption that the covariate is linearly related to the dependent variable is important in terms of ANCOVA's efficiency. That is, if the assumption is not met, the analysis will still be valid, but it will be no more powerful than regular analysis of variance. In fact, it may be slightly less powerful due to the loss of a degree of freedom for estimating the variance of the covariate.

The test of this assumption is very simple. One need only test the significance of the linear relationship between the covariate and the dependent variable. A significant relationship indicates the assumption is met. This can be tested by first computing a Pearson product-moment correlation coefficient followed by a t-test. Most computer library packages will print out a test of this assumption automatically.

Homogeneity of Regression

Indications are that the ANCOVA procedure is relatively robust with respect to violations of this assumption. Peckham (1970) conducted a computer simulation study of the robustness of ANCOVA to violations of the homogeneity of regression assumption. He indicated that two patterns emerged from his study. The first pattern is that "the empirical F distribution of the fixed-effects analysis of covariance closely approximates the normal theory F distribution for all but the most heterogeneous regression slopes" (p. 9) and the second is that "the test for the rejection of the null hypothesis becomes more conservative with respect to a Type I error as the heterogeneity of the regression slopes increase" (p. 9). Peckham (1970) concluded that "the results of this investigation indicate the analysis of covariance is robust to violations of the assumption of homogeneous regression slopes . . ." (p. 11).

This assumption is one of the more difficult to test. Some computer library packages provide a test within their regular analysis. McLean (1974, pp. 18-19) indicated through derivation that the group regression slopes were equal to their respective group covariate reliabilities in the case where a pretest was used as the covariate. Assuming that this proof is accurate, that would mean that if the reliabilities of the covariate measures were equivalent among the treatment groups, then the assumption of homogeneity of regression would be met. Since the reliability of an instrument is related so closely to the variability of the populations on which it is used, the assumption could be tested by comparing the covariate variances among the treatment groups. This test is a byproduct of the test of Assumption 2, concerning the independence of the covariate and treatment.

Although direct tests of the homogeneity of regression are available, in light of the findings of Peckham (1970) and the quick and dirty procedure indicated by McLean (1974), the direct test is not usually warranted. If extreme heterogeneity of regression is suspected, refer to Ferguson (1976) for a more complete description of a direct test.

Normal Distribution

Studies and authorities have indicated that ANCOVA is robust to most violations of the assumptions of normality (e.g., Cochran, 1957; Glass et al., 1972; Winer, 1971). Generally, this assumption should be given about the same attention when performing ANCOVA as when using analysis of variance or a t-test. If there is enough concern for a gross violation of this assumption, the researcher should consider a nonparametric procedure such as Kruskal-Wallis.

Homogeneity of Variance

This is another carry-over assumption from analysis of variance. It requires about the same amount of concern in ANCOVA as it does in analysis of variance. This assumption is very difficult to test precisely in ANCOVA because it would require testing separately the corresponding values of the dependent variable for each value of the covariate over the groups. Even if a large enough sample were available, the test would need to be repeated many times.

An alternate procedure is simply to test the homogeneity of variance of the dependent variable while ignoring the covariate, as is done in analysis of variance. This can be done using either Hartley's F-max or Bartlett's procedure (Kirk, 1968).

An Example

In order to put the preceding discussion in perspective, consider the following example:

Three fourth-grade classrooms in a middle-class suburban school were assigned randomly to one of three different reading methods. Students in Classroom 1 were taught according to a traditional reading program. Students in Classroom 2 were trained under the traditional program with extra emphasis on phonic methods of instruction. Students in Classroom 3 utilized the traditional program along with special training in the "look-say" method of reading instruction. At the end of a six-week period, students were given a reading comprehension test. The test scores together with the scholastic ability scores of the students are shown below:

Table 1

Data Relevant to Example

Reading Method					
Standard		Phonics		Look-Say	
Y	X	Y	X	Y	X
36	86	30	92	25	97
32	93	28	96	36	105
40	102	42	105	39	113
38	105	44	112	37	113
31	107	47	113	45	123
46	107	45	117	52	128
45	110	40	120	40	140

Y = scholastic ability.

X = reading comprehension.

These data were contrived for the purposes of this example and any relationship with reality is coincidental.

Suppose it is desired to compare the mean reading achievement of children taught under the three methods. ANCOVA can be used by taking into account the students' scholastic ability; that is, using scholastic ability as the covariate.

For purposes of this example the Statistical Package for the Social Sciences (SPSS) was used (Nie, Hull, Jenkins, Steinbrenner, & Bent, 1975). This computer library statistical package is available widely and is relatively easy to use. A copy of the program can be found in the Appendix. Note that the printout includes several analyses. These analyses (ANCOVA, ANOVA on covariate, and ANOVA on dependent variable) are necessary for testing the assumptions and completing the ANCOVA.

Tests of Assumptions

The first analyses to be performed in conjunction with ANCOVA are the tests of the assumptions. They are discussed here in the same order in which they were presented in the preceding section.

Random Assignment. This assumption is usually not tested but is designed into the procedures. It can be noted from the example that students were assigned randomly to the teaching methods.

Independence of covariate and treatment groups. As was noted in the discussion of this assumption, it can be tested by performing an analysis of variance on the covariate, ignoring the dependent variable. The analysis can be found on page 9 of the printout (Appendix) and is reproduced in Table 2.

Table 2

ANOVA Summary Table for Ability

Source	SS	DF	MS	F
Among Groups	4.95	2	2.48	.05 N.S.
Within Groups	956.00	18	53.11	
Total	960.95	20		

$F_{max} = 2.02$, N.S.

First, the homogeneity of variance assumption for that analysis was tested using the F_{max} procedure. This was found to be nonsignificant ($F_{max} = 2.02$, N.S.)

thus supporting the reasonableness of the analysis of variance. The groups were found not to be significantly different thus the assumption concerning the independence of the covariate and treatment groups can be considered reasonable.

Perfect reliability. As noted in the discussion of this assumption, no test is required if the instruments used had reasonable reliability.

Covariate related to dependent variable. This assumption can be tested directly using the SPSS program. An F-test of this assumption is found on page 2 of the printout (Appendix) under the source, covariate ($F(1,17) = 18.12$, $p < .001$).

It is interesting to note that sums of squares (SS) associated with the covariate and the total can be used to compute the linear correlation between the covariate and the dependent variable. $SS_{covariate}$ and SS_{total} represent the variability accounted for by the covariate and total respectively. Thus,

$$r = \sqrt{\frac{SS_{covariate}}{SS_{total}}} = \sqrt{\frac{1281.615}{3251.809}} = .6278.$$

This result is verified by comparing it with the Pearson correlation coefficient found on page 5 of the SPSS printout (Appendix).

Homogeneity of regression. A direct test of this assumption is rarely needed as was noted in earlier discussion. A quick and dirty test can be done by comparing the group covariate variances. This was done as a preliminary analysis for testing the covariate-treatment group independence assumption. The test statistic was found to be nonsignificant ($F_{max} = 2.02$, N.S.). Thus, the homogeneity of regression assumption can be accepted as reasonable.

Normal distribution. This assumption does not need to be tested. If an extreme violation of normality is expected, another type of analysis should be considered.

Homogeneity of variance. As noted in the earlier discussion, a reasonable test of this assumption is an F_{max} comparing the group variances of the dependent variable. In this case, the homogeneity of variance assumption is reasonable ($F_{max} = 2.76$, N.S.).

Summary. Thus, in this case, the ANCOVA assumptions are reasonable and the balance of the analysis can be completed.

Analysis of Covariance

The ANCOVA itself generally consists of completing a summary table followed by appropriate multiple comparison procedures if a significant among groups effect is found. Each is presented below.

ANCOVA summary table. The ANCOVA summary table is presented in Table 3. It can be found on page 2 of the SPSS printout (Appendix).

Table 3

ANCOVA Summary Table

Source	Adjusted SS	DF	Adjusted MS	Adjusted F
Covariate	1281.615	1	1281.615	18.12 ($p<.001$)
Among Groups	767.786	2	383.893	5.43 ($p<.05$)
Within Groups	1202.408	17	70.730	
Total	3251.809	20		

Based upon the adjusted F, ($F(2,17) = 5.43$, $p<.05$), the groups are taken to be significantly different. It is interesting to note that the regular analysis of variance without the covariate found on page 7 of the printout (Appendix) did not indicate among group differences ($F(2,18) = 3.22$, $p<.05$). Since the groups are significantly different, a multiple comparison procedure is needed to determine where the differences are.

<u>Multiple comparisons</u>. A significant among groups F-ratio with more than two groups requires further analysis to determine where the difference or differences actually are. The comparisons are made on the adjusted group means (Ferguson, 1976).

These adjusted group means can be found by using the information on page 3 of the printout (Appendix). The grand mean (108.76) is adjusted by adding the appropriate adjusted deviation (-6.59, -1.44, and 8.03 for each group respectively). Thus, the adjusted group means are 102.17, 107.32, and 116.79.

One appropriate multiple comparison procedure in this case is Tukey's Honestly Significant Difference (HSD) procedure (Kirk, 1968).

$$HSD = q\sqrt{\frac{MSD_{ADJ.}}{n}}$$

$$= 3.63\sqrt{\frac{70.73}{7}} = 11.54.$$

Thus, any difference greater than 11.54 can be considered significant at the .05 level. Table 4 indicates the among group differences.

Table 4

Adjusted Group Mean Difference

	Group		
Group	3	2	1
3	---	9.47	14.62*
2		---	5.15
1			---

HSD = 11.54.

*Significant at .05 level.

The only groups significantly different are Groups 1 and 3. Group 3 was found to have a significantly greater mean than Group 1.

Alternatives When Assumptions Are Not Met

The relative importance of each assumption was noted in an earlier section. If one or more of the critical assumptions are not met, other types of analysis should be considered.

The random assignment, normality, and homogeneity of variance assumptions should be considered in the same way one would consider them in analysis of variance. Gross violations of one or more of these assumptions would often require the use of a nonparametric procedure (which still requires random sampling) such as the Kruskal-Wallis Procedure (Ferguson, 1976). Concern over the effects of violations of the perfect reliability and homogeneity of regression assumptions may be minimized unless such violations are gross. In cases of gross violations, regular analysis of variance should be considered. Violations of the assumptions concerning the relationship between the covariate and dependent variable would only result in a slightly less powerful test.

If the covariate and treatment are dependent, one might arrive at a conclusion completely at odds with reality (McLean & Ware, 1977). A violation of this assumption should lead to a different analysis, such as analysis of variance.

If regular analysis of variance is considered as an alternative to ANCOVA, two designs can be considered. The first involves performing the analysis on the dependent variable and ignoring the covariate. The second involves using the covariate as a repeated measure in a repeated measure design. This is feasible if the covariate is a pretest score measured on the same instrument as the dependent variable. The latter analysis should be more powerful. An equivalent result could be obtained by performing a standard analysis of variance on the pre-to-post gain scores.

Summary

Analysis of covariances can be a very useful procedure if used correctly. Its correct usage requires the researcher to keep in mind the assumptions and their tests. As illustrated in this paper, ANCOVA can be performed very easily when the assumptions are kept in mind from the onset.

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APPENDIX

SPSS COMPUTER PRINTOUT

```
DEFAULT TRANSPACE ALLOCATION                                1125 WORDS

     MAX NO OF TRANSFORMATIONS PERMITTED              37
     MAX NO OF RECODE VALUES                         150
     MAX NO OF ARITHM.OR LOG.OPERATIONS              300

RESULTING WORKSPACE ALLOCATION                              7875 WORDS

1.        RUN NAME          MSERA EXAMPLE, GROUPS=METHOD OF INSTR, COV=ABILITY, DV=READ COMP
2.        VARIABLE LIST     GROUP,ABILITY,READCOMP
3.        INPUT MEDIUM      CARD
4.        N OF CASES        21
5.        INPUT FORMAT      FIXED(F1.0,F3.0,F4.0)

          ACCORDING TO YOUR INPUT FORMAT, VARIABLES ARE TO BE READ AS FOLLOWS

          VARIABLE   FORMAT   RECORD     COLUMNS

          GROUP      F 1. 0      1        1-   1
          ABILITY    F 3. 0      1        2-   4
          READCOMP   F 4. 0      1        5-   8

THE INPUT FORMAT PROVIDES FOR   3 VARIABLES.    3 WILL BE READ
IT PROVIDES FOR  1 RECORDS ('CARDS') PER CASE.  A MAXIMUM OF    8 'COLUMNS' ARE USED ON A RECORD.

6.        ANOVA             READCOMP BY GROUP(1,3) WITH ABILITY
7.        STATISTICS        1,3

'ANOVA' PROBLEM REQUIRES        77 WORDS OF SPACE.

8.        READ INPUT DATA
```

FILE NONAME (CREATION DATE = 01 OCT 79)

* * * * * * * * * * A N A L Y S I S   O F   V A R I A N C E * * * * * * * * * *

READCOMP
BY GROUP
WITH ABILITY

SOURCE OF VARIATION	SUM OF SQUARES	DF	MEAN SQUARE	F	SIGNIF OF F
COVARIATES	1281.615	1	1281.615	18.120	.001
ABILITY	1281.615	1	1281.615	18.120	.001
MAIN EFFECTS	767.786	2	383.893	5.428	.015
GROUP	767.786	2	383.893	5.428	.015
EXPLAINED	2049.402	3	683.134	9.658	.001
RESIDUAL	1202.408	17	70.730		
TOTAL	3251.809	20	162.590		

21 CASES WERE PROCESSED.
0 CASES (.0 PCT) WERE MISSING.

FILE NONAME (CREATION DATE = 01 OCT 79)

* * * M U L T I P L E C L A S S I F I C A T I O N A N A L Y S I S * * *

READCOMP
BY GROUP
WITH ABILITY

* *

GRAND MEAN = 108.76

VARIABLE + CATEGORY	N	UNADJUSTED DEV'N	UNADJUSTED ETA	ADJUSTED FOR INDEPENDENTS DEV'N	ADJUSTED FOR INDEPENDENTS BETA	ADJUSTED FOR INDEPENDENTS + COVARIATES DEV'N	ADJUSTED FOR INDEPENDENTS + COVARIATES BETA
GROUP							
1	7	-7.33				-6.59	
2	7	-.90				-1.44	
3	7	8.24				8.03	
			.51				.49

MULTIPLE R SQUARED	.630
MULTIPLE R	.794

DATA TRANSFORMATION DONE UP TO THIS POINT..

NO OF TRANSFORMATIONS	0
NO OF RECODE VALUES	0
NO OF ARITHM. OR LOG. OPERATIONS	0
THE AMOUNT OF TRANSPACE REQUIRED IS	0 WORDS

9. PEARSON CORR ABILITY WITH READCOMP

***** PEARSON CORR PROBLEM REQUIRES 12 WORDS WORKSPACE *****

FILE NONAME (CREATION DATE = 01 OCT 79)

- - - - - - - - - - P E A R S O N C O R R E L A T I O N C O E F F I C I E N T S - - - - - - - - - -

	READCOMP
ABILITY	.6278
	(21)
	S= .001

(COEFFICIENT / (CASES) / SIGNIFICANCE) (A VALUE OF 99.0000 IS PRINTED IF A COEFFICIENT CANNOT BE COMPUTED)

```
10.     ONEWAY        READCOMP BY GROUP(1,3)
11.     STATISTICS    1,3
```

***** ONEWAY PROBLEM REQUIRES 28 WORDS WORKSPACE *****

FILE NONAME (CREATION DATE = 01 OCT 79)

- O N E W A Y -

VARIABLE READCOMP

ANALYSIS OF VARIANCE

SOURCE	D.F.	SUM OF SQUARES	MEAN SQUARES	F RATIO	F PROB.
BETWEEN GROUPS	2	857.2363	428.6182	3.222	.063
WITHIN GROUPS	18	2394.5742	133.0319		
TOTAL	20	3251.8105			

GROUP	COUNT	MEAN	STANDARD DEVIATION	STANDARD ERROR	MINIMUM	MAXIMUM	95 PCT CONF INT FOR MEAN
GRP01	7	101.4286	8.7342	3.3012	86.0000	110.0000	93.3509 TO 109.5063
GRP02	7	107.6571	10.6055	4.0085	92.0000	120.0000	98.0488 TO 117.6655
GRP03	7	117.0000	14.5029	5.4816	97.0000	140.0000	103.5872 TO 130.4128
TOTAL	21	108.7619	12.7511	2.7825	86.0000	140.0000	102.9577 TO 114.5661

TESTS FOR HOMOGENEITY OF VARIANCES

COCHRANS C = MAX. VARIANCE/SUM(VARIANCES) = .5270, P = .223 (APPROX.)
BARTLETT-BOX F = .742, P = .481
MAXIMUM VARIANCE / MINIMUM VARIANCE = 2.757

```
12.     ONEWAY        ABILITY BY GROUP(1,3)
13.     STATISTICS    1,3

***** ONEWAY PROBLEM REQUIRES      28 WORDS WORKSPACE *****
```

FILE NONAME (CREATION DATE = 01 OCT 79)

- O N E W A Y -

VARIABLE ABILITY

ANALYSIS OF VARIANCE

SOURCE	D.F.	SUM OF SQUARES	MEAN SQUARES	F RATIO	F PROB.
BETWEEN GROUPS	2	4.9524	2.4762	.047	.944
WITHIN GROUPS	18	956.0005	53.1111		
TOTAL	20	960.9526			

GROUP	COUNT	MEAN	STANDARD DEVIATION	STANDARD ERROR	MINIMUM	MAXIMUM	95 PCT CONF INT FOR MEAN
GRP01	7	38.2857	5.8513	2.2116	31.0000	46.0000	32.8742 TO 43.6973
GRP02	7	39.4286	7.4801	2.8272	28.0000	47.0000	32.5106 TO 46.3465
GRP03	7	39.1429	8.3152	3.1429	25.0000	52.0000	31.4526 TO 46.8331
TOTAL	21	38.9524	6.9316	1.5126	25.0000	52.0000	35.7971 TO 42.1076

TESTS FOR HOMOGENEITY OF VARIANCES

COCHRANS C = MAX. VARIANCE/SUM(VARIANCES) = .4340, P = .497 (APPROX.)
BARTLETT-BOX F = .343, P = .714
MAXIMUM VARIANCE / MINIMUM VARIANCE = 2.019

25